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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53 (c).

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☐ *Additional inventors are being named on the _____ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (280 characters max)

Fast 3-D Surface Multiple Prediction (3D-FSMP)

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ENCLOSED APPLICATION PARTS ***(check all that apply)***

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☐ Application Data Sheet. See 37 CFR 1.76

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

☐ Applicant claims small entity status. See 37 CFR 1.27.

☐ A check or money order is enclosed to cover the filing fees

☒ The Commissioner is hereby authorized to charge filing fees or credit any overpayment to Deposit Account Number: 20-0782/WGEC/0028L/WBP

FILING FEE AMOUNT ($) 160.00

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The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☒ No.

☐ Yes, the name of the U.S. Government agency and the Government contract number are: _____.

Respectfully submitted,
SIGNATURE Ari Pramudji

Date 04/07/04

REGISTRATION NO. (*if appropriate*) 45,022

TYPED or PRINTED NAME Ari O. Pramudji

Docket Number: WGEC/0028L

TELEPHONE 713/623-4844

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

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UNITED STATES PATENT APPLICATION FOR:

FAST 3-D SURFACE MULTIPLE PREDICTION

INVENTORS:

IAN MOORE

RICHARD BISLEY

ATTORNEY DOCKET NUMBER: 594-25606 WGEC/0028L

CERTIFICATION OF MAILING UNDER 37 C.F.R. 1.10

I hereby certify that this New Application and the documents referred to as enclosed therein are being deposited with the United States Postal Service on April 7, 2004, in an envelope marked as "Express Mail United States Postal Service", Mailing Label No. EV416703285US, addressed to: Mail Stop PATENT APPLICATION, Commissioner for Patents, P.O. Box 1450, Alexandria, VA. 22313-1450.

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FAST 3-D SURFACE MULTIPLE PREDICTION

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] Embodiments of the present invention generally relate to marine seismic surveying and, more particularly, to a method for attenuating the effect of surface multiples in a marine seismic signal.

Description of the Related Art

[0002] Seismic surveying is a method for determining the structure of subterranean formations in the earth. Seismic surveying typically utilizes seismic energy sources which generate seismic waves and seismic receivers which detect seismic waves. The seismic waves propagate into the formations in the earth, where a portion of the waves reflects from interfaces between subterranean formations. The amplitude and polarity of the reflected waves are determined by the differences in acoustic impedance between the rock layers comprising the subterranean formations. The acoustic impedance of a rock layer is the product of the acoustic propagation velocity within the layer and the density of the layer. The seismic receivers detect the reflected seismic waves and convert the reflected waves into representative electrical signals. The signals are typically transmitted by electrical, optical, radio or other means to devices which record the signals. Through analysis of the recorded signals (or traces), the shape, position and composition of the subterranean formations can be determined.

[0003] Marine seismic surveying is a method for determining the structure of subterranean formations underlying bodies of water. Marine seismic surveying typically utilizes seismic energy sources and seismic receivers located in the water which are either towed behind a vessel or positioned on the water bottom from a vessel. The energy source is typically an explosive device or compressed air system which generates seismic energy, which then propagates as seismic waves through the body of water and into the earth formations below the bottom of the water. As the seismic waves strike interfaces between subterranean formations, a

portion of the seismic waves reflects back through the earth and water to the seismic receivers, to be detected, transmitted, and recorded. The seismic receivers typically used in marine seismic surveying are pressure sensors, such as hydrophones. Additionally, though, motion sensors, such as geophones or accelerometers may be used. Both the sources and receivers may be strategically repositioned to cover the survey area.

[0004] Seismic waves, however, reflect from interfaces other than just those between subterranean formations, as would be desired. Seismic waves also reflect from the water bottom and the water surface, and the resulting reflected waves themselves continue to reflect. Waves which reflect multiple times are called "multiples". Waves which reflect multiple times in the water layer between the water surface above and the water bottom below are called "water-bottom multiples". Water-bottom multiples have long been recognized as a problem in marine seismic processing and interpretation, so multiple attenuation methods based on the wave equation have been developed to handle water-bottom multiples. However, a larger set of multiples containing water-bottom multiples as a subset can be defined. The larger set includes multiples with upward reflections from interfaces between subterranean formations in addition to upward reflections from the water bottom. The multiples in the larger set have in common their downward reflections at the water surface and thus are called "surface multiples". Figure 1, discussed below, provides examples of different types of reflections.

[0005] Figure 1 shows a diagrammatic view of marine seismic surveying. The procedure is designated generally as 100. Subterranean formations to be explored, such as 102 and 104, lie below a body of water 106. Seismic energy sources 108 and seismic receivers 110 are positioned in the body of water 106, typically by one or more seismic vessels (not shown). A seismic source 108, such as an air gun, creates seismic waves in the body of water 106 and a portion of the seismic waves travels downward through the water toward the subterranean formations 102 and 104 beneath the body of water 106. When the seismic waves reach a seismic reflector, a portion of the seismic waves reflects upward and a portion of the seismic

waves continues downward. The seismic reflector can be the water bottom 112 or one of the interfaces between subterranean formation, such as interface 114 between formations 102 and 104. When the reflected waves traveling upward reach the water/air interface at the water surface 116, a majority portion of the waves reflects downward again. Continuing in this fashion, seismic waves can reflect multiple times between upward reflectors, such as the water bottom 112 or formation interfaces below, and the downward reflector at the water surface 116 above, as described more fully below. Each time the reflected waves propagate past the position of a seismic receiver 110, the receiver 110 senses the reflected waves and generates representative signals.

[0006] Primary reflections are those seismic waves which have reflected only once, from the water bottom 112 or an interface between subterranean formations, before being detected by a seismic receiver 110. An example of a primary reflection is shown in FIG. 1 by raypaths 120 and 122. Primary reflections contain the desired information about the subterranean formations which is the goal of marine seismic surveying. Surface multiples are those waves which have reflected multiple times between the water surface 116 and any upward reflectors, such as the water bottom 112 or formation interfaces, before being sensed by a receiver 110. An example of a surface multiple which is specifically a water bottom multiple is shown by raypaths 130, 132, 134 and 136. The point on the water surface 116 at which the wave is reflected downward for the second time is generally referred to as the downward reflection point. The surface multiple starting at raypath 130 is a multiple of order one, since the multiple contains one reflection from the water surface 116. Two examples of general surface multiples with upward reflections from both the water bottom 112 and formation interfaces are shown by raypaths 140, 142, 144, 146, 148 and 150 and by raypaths 160, 162, 164, 166, 168 and 170. Both of these latter two examples of surface multiples are multiples of order two, since the multiples contain two reflections from the water surface 116. In general, a surface multiple is of order i if the multiple contains i reflections from the water surface 116. Surface multiples are extraneous noise which obscures the desired primary reflection signal.

[0007] Surface multiple attenuation is a prestack inversion of a recorded wavefield which removes all orders of all surface multiples present within the marine seismic signal. Unlike some wave-equation-based multiple-attenuation algorithms, surface multiple attenuation does not require any modeling of or assumptions regarding the positions, shapes and reflection coefficients of the multiple-causing reflectors. Instead, surface multiple attenuation relies on the internal physical consistency between primary and multiple events that must exist in any properly recorded marine data set. The information needed for the surface multiple attenuation process is already contained within the seismic data.

[0008] Various prior art methods have been tried for removal of surface multiples from recorded traces. It has been noted, for example, that the travel time for a surface multiple, the path of which is entirely in the water during an oceanographic expedition, is a function of the "offset", the distance between the source and receiver, and the number of times the multiple reflects from the surface. For example, if the multiple reflects from the surface once before being received by the microphone and the offset is zero, the multiple's travel time is exactly twice that of the principal waves. This fact has been used in various schemes to remove multiples.

[0009] Other methods involve complex ray tracing schemes which generate a synthetic multiple wave and subtract it from the actual wave to obtain a supposedly multiple free record. However, these methods are very awkward in that they require significant knowledge of the subsea structure as well as the ocean bottom configuration before the synthetic wave can be generated. Similar synthetic multiples can be generated using more accurate methods not directly involving ray tracing, e.g., field propagation techniques, but again these require detailed knowledge of at least the ocean bottom, as well as the shape of the subsea interfaces, and so are not as practical as would be desired.

[0010] Therefore, a need exists in the art for an improved method for removing the record of multiple surface reflection events from seismic records for data processing purposes.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The following detailed description makes reference to the accompanying drawings, which are now briefly described.

[0012] Figure 1 illustrates a diagrammatic view of marine seismic surveying.

[0013] Figure 2 illustrates a plan view of the geometry.

[0014] Figure 3 illustrates a flow diagram using 3D FSMP described herein in accordance with one embodiment of the invention.

[0015] Figure 4 illustrates a flow diagram using 3D FSMP described herein in accordance with another embodiment of the invention.

[0016] Figure 5 illustrates a computer network into which embodiments of the invention may be implemented.

DESCRIPTION OF THE INVENTION

[0017] The following references listed below may provide additional background, definitions and support for the present invention:

- US Patent Application Serial No. 10/668,927 issued to Moore, entitled "Method for the 3D Prediction of Free Surface Multiples."
- Levin, S. A., 2002, Prestack poststack 3D multiple prediction: 72nd Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, SP3-05.
- PCT Patent Application No. PCT/US2003/039310 entitled "Method for Computing and Using Timing Errors that Occur in Multiples Predicted by Multiple Prediction Algorithm."

3D FSMP (fast surface-related multiple prediction)

[0018] 3D FSMP is a fast implementation of the 3D surface-related multiple prediction (SMP) algorithm. The improved performance is attained by making some approximations in the derivation of the algorithm. Theory and tests have shown that, in many cases, the predicted multiples are still sufficiently accurate that they may be adaptively subtracted. When crossline dip effects are significant, multiples predicted using 3D FSMP will be much more accurate than those predicted by a 2D algorithm.

[0019] 3D FSMP is also capable of accounting for irregularities in the acquisition geometry, in particular those due to cable feathering, when predicting multiples. When feather is significant, this is often very important. Note however that 3D FSMP, like all other prediction algorithms, requires a reasonably well-sampled recorded dataset on which to base the prediction.

[0020] The 3D FSMP method:

- provides a reasonably accurate prediction for these simple models
- can target the required azimuth
- is more accurate than conventional SMP when

  feather is significant, and

  multiple travel time depends significantly on azimuth.

[0021] The proposed method, known as 3D Fast Surface Multiple Prediction (3D FSMP), predicts surface multiples in a manner similar to 3D SMP, but at greatly reduced cost. There are some additional assumptions, which are best met in deep-water situations and for first-order multiples. The method can predict multiples at a specified azimuth and can therefore be made to account for azimuth variations in the data. These azimuth variations can be a significant source of error in predicted multiples. It is also possible to predict the errors associated with this prediction

method, in a similar manner to that which is done for 2D and 3D SMP, described in US Patent Application Serial No. 10/668,927 referenced above.

Theoretical derivation

[0022] In the following, 3D SRME refers to a general implementation of SRME yielding a 3D prediction and 3D FSMP refers to the new method described here.

[0023] Figure 2 shows the plan view of the geometry. Suppose we wish to predict surface multiples for the trace with source at S and receiver at R, henceforth denoted (S,R). Define M and h to be the midpoint and offset of (S,R) respectively, as shown in the figure. Let X be a potential downward reflection point (DRP) for the surface multiples.

[0024] 3D SRME is in general implemented by convolving the trace (S,X) with the trace (X,R), and summing these convolutions over all possible X. In order to do this, the traces (S,X) and (X,R) generally need to be estimated from recorded traces. One way to estimate the trace (S,X) is to apply a differential moveout correction to the trace with the same midpoint, M_S, from the recorded dataset, and with similar offset (Moore, 2003), as in 3D SMP. The trace (X,R) can be estimated similarly. The differential moveout applied to the recorded trace depends not only on its offset, but also on the offset from S to X, denoted x_S in the figure. Typically a given recorded trace will only be used to estimate one trace per subsurface line (SSL) in the prediction process, but it will be used on every SSL within a given aperture of the recorded trace. This means that the differential moveout correction and convolution must be repeated for every SSL for which the prediction is required.

[0025] Suppose that we could swap the order of the moveout correction and the convolution, i.e. we could convolve traces with midpoints at M_S and M_R before applying any moveout correction, and we then try to correct for the resultant error after convolution. Suppose also that we use recorded traces that have been processed to approximate (kinematically) zero-offset traces at the midpoint locations. For a simple, first-order multiple from a horizontal reflector at time t_0 in a constant velocity medium with velocity v, the primary reflections occur at time t_0 on

the zero-offset traces at M_S and M_R, and at time $2t_0$ on their convolution. The travel time for the primary reflection on the trace (S,X) is given by

$$t(S,X) = [t_0^2 + (x_S/v)^2]^{1/2} \tag{1}$$

and similarly for the trace (X,R), such that the travel time on the convolution of these traces is given by

$$t(X) = [t_0^2 + (x_S/v)^2]^{1/2} + [t_0^2 + (x_R/v)^2]^{1/2} \tag{2}$$

[0026] We therefore need a post-convolution correction process that maps an event at time $2t_0$ to time $t(X)$. At this point we note that a constant velocity demigration operator with velocity V maps a migrated time t_m to a demigrated time t_d given by

$$t_d = [(t_m/2)^2 + (X_S/V)^2]^{1/2} + [(t_m/2)^2 + (X_R/V)^2]^{1/2} \tag{3}$$

where X_S and X_R are the distances from the migrated location to the demigrated source and receiver locations, respectively. This equation has very similar form to the correction that we require. If we put $t_m = 2t_0$ and $t_d = t(X)$, then we get

$$t(X) = [t_0^2 + (X_S/V)^2]^{1/2} + [t_0^2 + (X_R/V)^2]^{1/2} \tag{4}$$

[0027] This would be identical to the required correction if we located the convolved trace at X, and set $X_S = x_S$, $X_R = x_R$ and $V = v$. However the location X depends on S and R, and hence the demigration would have to be repeated whenever a change in (S,R) creates a change in X. Suppose we locate the convolved trace at the "migrated location" M_X, this being the midpoint of M_S and M_R, which does not depend on S or R, but only on M_S and M_R. If we define S' and R' to be the midpoints of SM and MR respectively, then we note that the distances from M_X to S' and R' are $x_S/2$ and $x_R/2$ respectively. Hence demigration from M_X to (S',R') yields a demigrated traveltime given by equation (3) with $X_S = x_S/2$ and $X_R = x_R/2$. This then gives the desired demigrated traveltime if we use a velocity $V = v/2$.

[0028] Note that $M_S M_R$ is parallel to SR, and the offset from M_S to M_R is *h*/2. Therefore if we fix the offset and azimuth of (S,R), then the offset and azimuth of $M_S M_R$ is also known. If we have a volume of data that has been kinematically mapped to zero offset, then given M_X, we can determine M_S and M_R, and convolve the corresponding traces from this volume, placing the convolution into a new volume at location M_X. Simply repeating this operation for all M_X, and then demigrating the volume at constant offset (*h*/2) and azimuth (as defined previously) with velocity *v*/2 yields the predicted multiples for the entire offset plane. This procedure constitutes the 3D FSMP process.

[0029] There are similarities between this method and the method proposed by Levin (2002), in that they both provide a 3D prediction starting from zero-offset data. Levin's method simulates the traces required for a conventional 3D SRME prediction by applying inverse moveout to the zero-offset data. The method described in the paper is formulated to obtain a zero-offset prediction, but it is easily extended to prestack data. The 3D FSMP method is fundamentally different to this and any of the other previously proposed 3D SRME methods in that it convolves traces before correcting for offset.

[0030] It is clear that the azimuth at which the multiples should be predicted can be easily targeted with 3D FSMP. If a given offset plane contains a range of azimuths, then the process can be repeated at a number of azimuths to cover this range, and the resultant traces interpolated across azimuth to provide a prediction at the required azimuth for each trace in the offset plane. Since the sensitivity of the predicted multiples to azimuth generally increases with offset, it is expected that the number of azimuths would increase as offset increases.

[0031] <u>**Cost**</u>

[0032] The main advantage of the process is its cost, compared to conventional implementations of 3D SRME. For each common offset, common azimuth volume, all that is required is a number of convolutions sufficient to fill the volume, followed by a single, constant velocity demigration.

Assumptions and error analysis

[0033] The derivation of the method assumed zero-dip and constant velocity, both of which are approximations to the real situation. Since the prediction process is simple, it is relatively easy to predict the errors associated with these assumptions, and code has been written to do this. Some results for multiples from a dipping planar reflector and for diffracted multiples have been obtained. The main conclusions are as follows:

1. The timing errors in the predicted multiples for 3D FSMP are often of a similar order of magnitude to those for 3D SMP, especially when feather is significant. Note that 3D SMP could be made to target a specific azimuth by running it over a range of azimuths, but in practice this would be extremely expensive. It is the greatly reduced cost of 3D FSMP that makes it practical in this case.

2. The errors for 3D FSMP increase as the inline dip (component of dip parallel to the trace) increases. 3D SMP handles inline dip accurately, whereas 3D FSMP is an approximation even in the 2D case.

[0034] The derivation of 3D FSMP has not taken amplitudes into account, whereas 3D SMP theoretically predicts first-order multiples with correct amplitudes. For symmetrical surface multiples and low structural dip, it is expected that the amplitude of the predicted multiple depends on the amplitude of the corresponding primaries at half the offset. For this reason, it is expected that the amplitudes of the predicted multiples at a given offset will be optimized in the 3D FSMP process by convolving data from half that offset.

Variations

[0035] There are many variations to the method described above that could be useful in practice, and which should be covered by the patent. These include:

1. Methods for computing the zero-offset section used as input for the prediction at a given offset. This can be subdivided into:

a) Choice of the input data. As mentioned above, a natural choice is data at half the required offset, though in principle any offset can be used. Alternatively, several offsets could be merged and/or sub-stacked to improve sampling and signal to noise ratio.
b) Mapping of the input data to zero offset. There are many methods for doing this, ranging from a simple moveout correction, to a full migration/demigration which also handles the azimuth of the input data. There are also options for the choice of velocity.

2. Methods for performing the half-offset demigration. There are many options here, ranging from a poststack (zero-offset) demigration followed by inv DMO and/or inverse moveout correction, to a full common-offset demigration. There is also a choice of velocity.

3. Figure 4 illustrates the embodiment described in this paragraph. The procedure described above convolves traces at zero-offset and then performs a demigration. It is also possible to convolve the traces at their original offset, and then correct the convolution before doing the demigration. This correction can be approximately achieved using moveout correction with half the velocity (or twice the offset). If some information about structural dip is known, taking this into account and convolving traces with different offsets, such that the downward reflection point is correctly located, may yield a better result. If the structural dip is unknown, its effect may still be accounted for (albeit at extra cost) by convolving all potential pairs of traces corresponding to all possible dips, and summing the convolutions. This process is then equivalent to a 2D surface multiple prediction.

[0036] Figure 5 illustrates a computer network 500, into which embodiments of the invention may be implemented. The computer network 500 includes a system computer 530, which may be implemented as any conventional personal computer or workstation, such as a UNIX-based workstation. The system computer 530 is in communication with disk storage devices 529, 531, and 533, which may be external hard disk storage devices. It is contemplated that disk storage devices 529, 531, and 533 are conventional hard disk drives, and as such, will be implemented by way of a local area network or by remote access. Of course, while disk storage devices

529, 531, and 533 are illustrated as separate devices, a single disk storage device may be used to store any and all of the program instructions, measurement data, and results as desired.

[0037] In one embodiment, seismic data from geophones are stored in disk storage device 531. The system computer 530 may retrieve the appropriate data from the disk storage device 531 to perform the 3-D surface multiple prediction according to program instructions that correspond to the methods described herein. The program instructions may be written in a computer programming language, such as C++, Java and the like. The program instructions may be stored in a computer-readable memory, such as program disk storage device 533. Of course, the memory medium storing the program instructions may be of any conventional type used for the storage of computer programs, including hard disk drives, floppy disks, CD-ROMs and other optical media, magnetic tape, and the like.

[0038] According to the preferred embodiment of the invention, the system computer 530 presents output primarily onto graphics display 527, or alternatively via printer 528. The system computer 530 may store the results of the methods described above on disk storage 529, for later use and further analysis. The keyboard 526 and the pointing device (e.g., a mouse, trackball, or the like) 525 may be provided with the system computer 530 to enable interactive operation.

[0039] The system computer 530 may be located at a data center remote from the survey region. The system computer 530 is in communication with geophones (either directly or via a recording unit, not shown), to receive signals indicative of the reflected seismic energy. These signals, after conventional formatting and other initial processing, are stored by the system computer 530 as digital data in the disk storage 531 for subsequent retrieval and processing in the manner described above. While Figure 5 illustrates the disk storage 531 as directly connected to the system computer 530, it is also contemplated that the disk storage device 531 may be accessible through a local area network or by remote access. Furthermore, while disk storage devices 529, 531 are illustrated as separate devices for storing input

seismic data and analysis results, the disk storage devices 529, 531 may be implemented within a single disk drive (either together with or separately from program disk storage device 533), or in any other conventional manner as will be fully understood by one of skill in the art having reference to this specification.

[0040] While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

264895_1

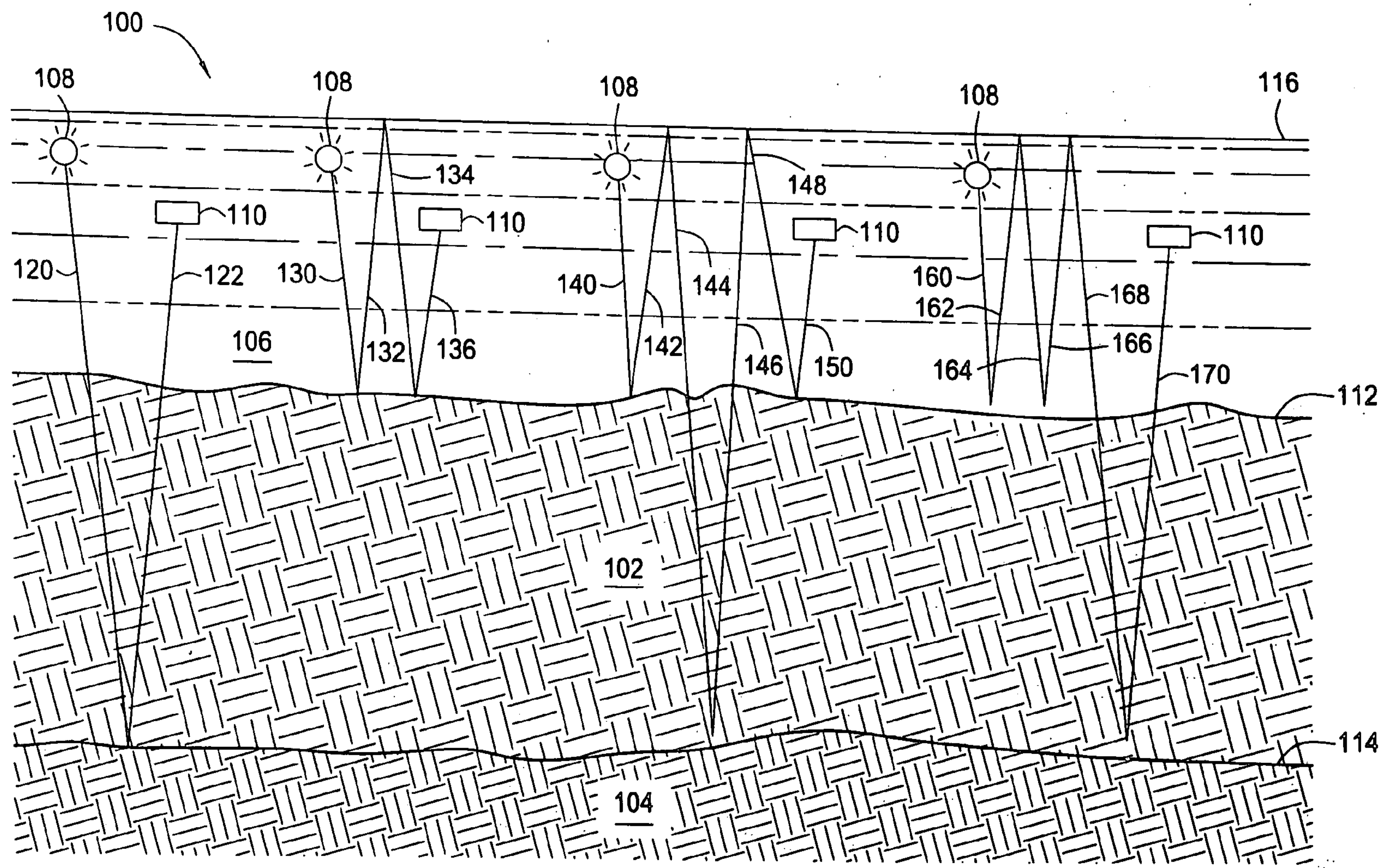


FIG. 1
(PRIOR ART)

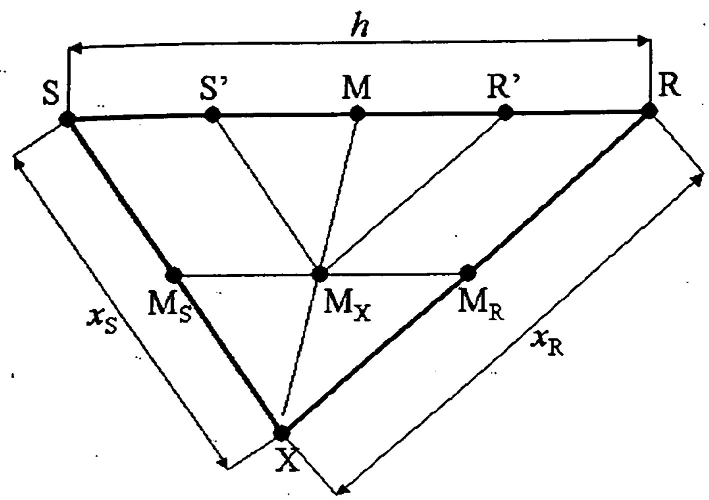
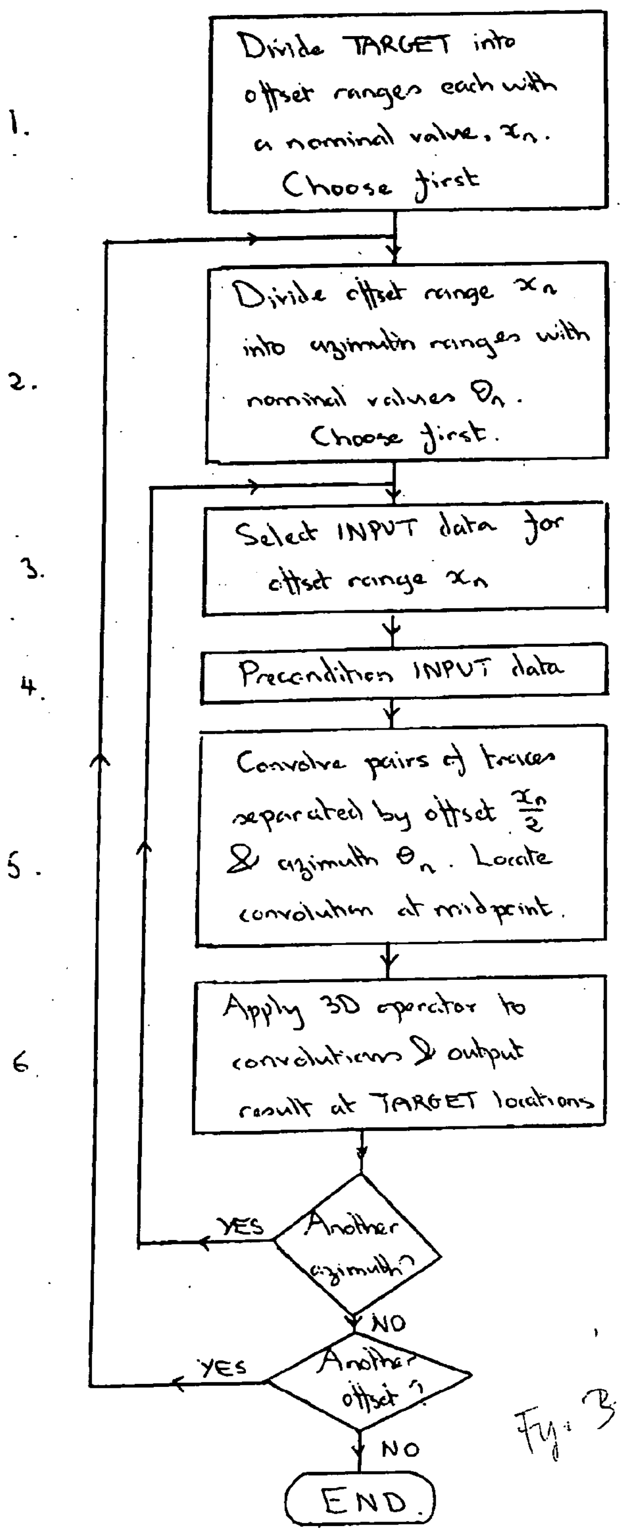


Figure 2: **Plan view of the geometry.**

2 Datasets :

1. TARGET. Header dataset defining locations for predicted multiples.
2. INPUT. Recorded data, generally after interpolation & regularization.



Azimuth range depends on x_n

Generally taken at offset $x_n/2$

e.g. moveout correction

Trace locations are defined by midpoints

e.g. demigration with offset $\frac{x_n}{2}$ & velocity $\frac{V_w}{2}$ for marine
V_w = water velocity.

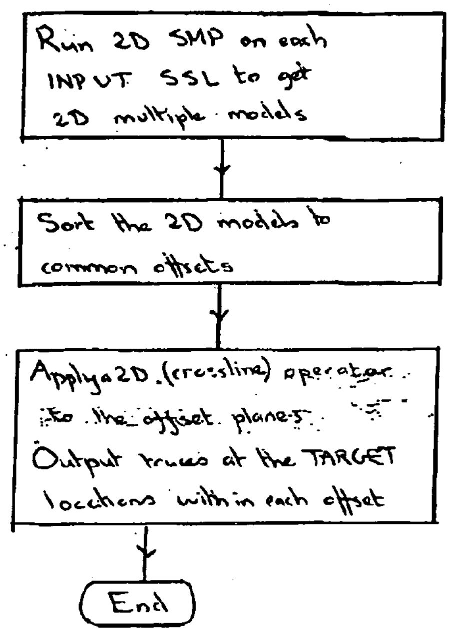
Steps 3 & 4 can be done before step 2 if they do not depend on azimuth.

Fig. 3

3D FSMP variation

2 Datasets

1. TARGET . Header dataset defining locations for predicted multiples
2. INPUT . Recorded data, generally ordered as sub-surface lines (SSL's)



eg. 2D demigration with half primary velocity
Usually use half the water velocity.

Fig. 4

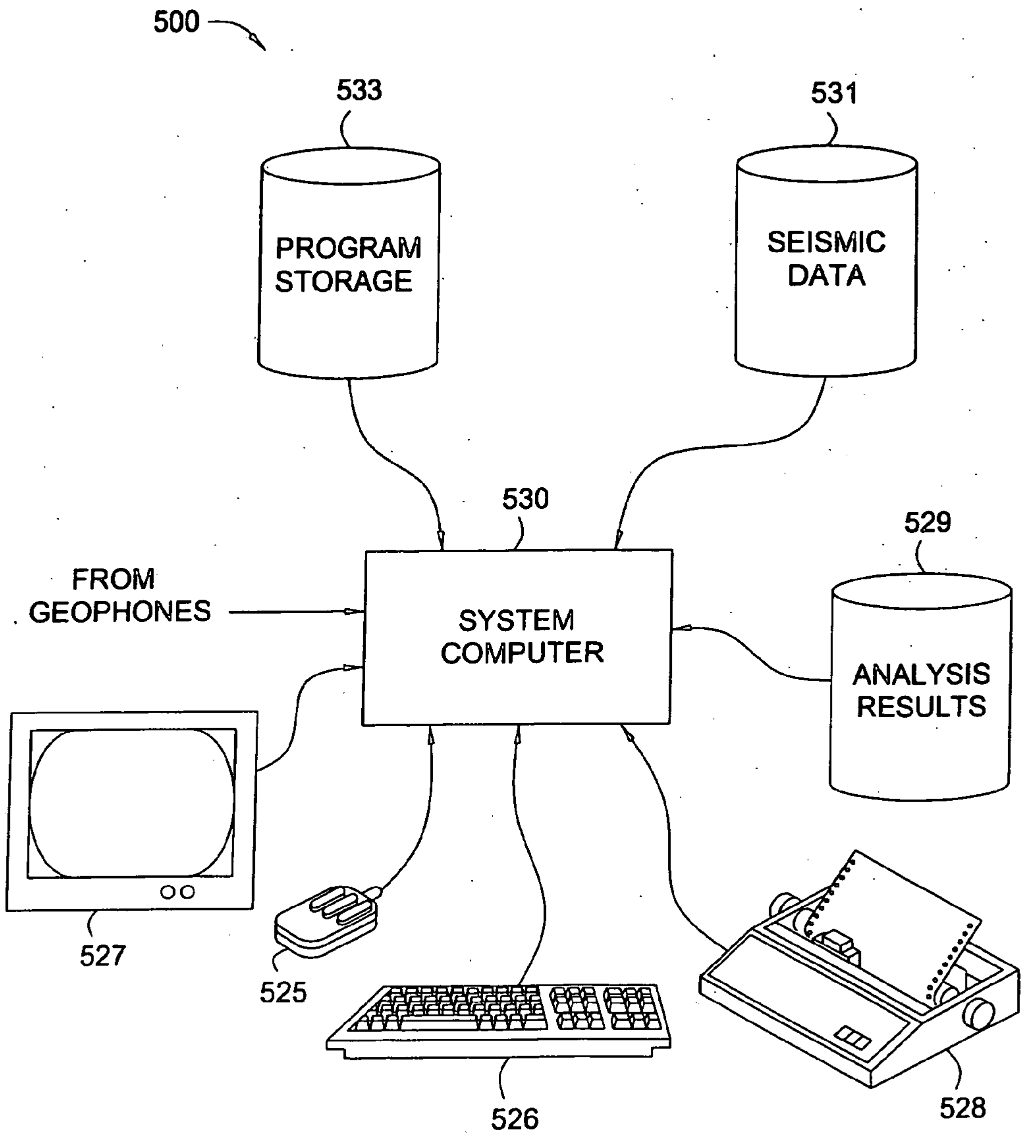

500
533
PROGRAM STORAGE
531
SEISMIC DATA
530
SYSTEM COMPUTER
FROM GEOPHONES
529
ANALYSIS RESULTS
527
525
526
528

FIG. 5